

09/484799

LITHIUM-BASED ACTIVE MATERIALS AND PREPARATION THEREOF

Field of the Invention

5 This invention relates to improved materials
usable as electrode active materials and to their
preparation.

Background of the Invention

10 Lithium batteries are prepared from one or more
lithium electrochemical cells containing
electrochemically active (electroactive) materials. Such
cells typically include an anode (negative electrode), a
cathode (positive electrode), and an electrolyte
interposed between spaced apart positive and negative
15 electrodes. Batteries with anodes of metallic lithium
and containing metal chalcogenide cathode active material
are known. The electrolyte typically comprises a salt of
lithium dissolved in one or more solvents, typically
nonaqueous (aprotic) organic solvents. Other
20 electrolytes are solid electrolytes typically called
polymeric matrixes that contain an ionic conductive
medium, typically a metallic powder or salt, in
combination with a polymer that itself may be ionically
conductive which is electrically insulating. By
25 convention, during discharge of the cell, the negative
electrode of the cell is defined as the anode. Cells
having a metallic lithium anode and metal chalcogenide
cathode are charged in an initial condition. During
discharge, lithium ions from the metallic anode pass
30 through the liquid electrolyte to the electrochemical

00870"66248450

2

active (electroactive) material of the cathode whereupon they release electrical energy to an external circuit.

It has recently been suggested to replace the lithium metal anode with an insertion anode, such as a lithium metal chalcogenide or lithium metal oxide. Carbon anodes, such as coke and graphite, are also insertion materials. Such negative electrodes are used with lithium- containing insertion cathodes, in order to form an electroactive couple in a cell. Such cells, in an initial condition, are not charged. In order to be used to deliver electrochemical energy, such cells must be charged in order to transfer lithium to the anode from the lithium- containing cathode. During discharge the lithium is transferred from the anode back to the cathode. During a subsequent recharge, the lithium is transferred back to the anode where it re-inserts. Upon subsequent charge and discharge, the lithium ions (Li^+) are transported between the electrodes. Such rechargeable batteries, having no free metallic species are called rechargeable ion batteries or rocking chair batteries. See U.S. Patent Nos. 5,418,090; 4,464,447; 4,194,062; and 5,130,211.

Preferred positive electrode active materials include LiCoO_2 , LiMn_2O_4 , and LiNiO_2 . The cobalt compounds are relatively expensive and the nickel compounds are difficult to synthesize. A relatively economical positive electrode is LiMn_2O_4 , for which methods of synthesis are known. The lithium cobalt oxide (LiCoO_2), the lithium manganese oxide (LiMn_2O_4), and the lithium nickel oxide (LiNiO_2) all have a common disadvantage in that the charge capacity of a cell comprising such cathodes suffers a significant loss in capacity. That


is, the initial capacity available (amp hours/gram) from LiMn_2O_4 , LiNiO_2 , and LiCoO_2 is less than the theoretical capacity because significantly less than 1 atomic unit of lithium engages in the electrochemical reaction. Such an initial capacity value is significantly diminished during the first cycle operation and such capacity further diminishes on every successive cycle of operation. For LiNiO_2 and LiCoO_2 only about 0.5 atomic units of lithium is reversibly cycled during cell operation. Many attempts have been made to reduce capacity fading, for example, as described in U.S. Patent No. 4,828,834 by Nagaura et al. However, the presently known and commonly used, alkali transition metal oxide compounds suffer from relatively low capacity. Therefore, there remains the difficulty of obtaining a lithium-containing electrode material having acceptable capacity without disadvantage of significant capacity loss when used in a cell.

00870 554860

Summary of the Invention

The invention provides novel lithium-mixed metal materials which, upon electrochemical interaction, release lithium ions, and are capable of reversibly cycling lithium ions. The invention provides a rechargeable lithium battery which comprises an electrode formed from the novel lithium-mixed metal materials. Methods for making the novel lithium-mixed metal materials and methods for using such lithium-mixed metal materials in electrochemical cells are also provided. The lithium-mixed metal materials comprise lithium and at least one other metal besides lithium. Preferred materials are lithium-mixed metal phosphates which contain lithium and two other metals besides lithium. Accordingly, the invention provides a rechargeable lithium battery which comprises an electrolyte; a first electrode having a compatible active material; and a second electrode comprising the novel materials. In one aspect, the novel materials are lithium-mixed metal phosphates which preferably used as a positive electrode active material, reversibly cycle lithium ions with the compatible negative electrode active material. Desirably, the lithium-mixed metal phosphate is represented by the nominal general formula $\text{Li}_a\text{MI}_b\text{MII}_c(\text{PO}_4)_d$. Such compounds include $\text{Li}_1\text{MI}_a\text{MII}_b\text{PO}_4$ and $\text{Li}_3\text{MI}_a\text{MII}_b(\text{PO}_4)_3$; therefore, in an initial condition $0 \leq a \leq 1$ or $0 \leq a \leq 3$, respectively. During cycling, x quantity of lithium is released where $0 \leq x \leq a$. In the general formula, the sum of b plus c is up to about 2. Specific examples are $\text{Li}_1\text{MI}_{1-y}\text{MII}_y\text{PO}_4$ and $\text{Li}_3\text{MI}_{2-y}\text{MII}_y(\text{PO}_4)_3$.

In one aspect, MI and MII are the same. In a preferred aspect, MI and MII are different from one



009484799-011800

another. At least one of MI and MII is an element capable of an oxidation state higher than that initially present in the lithium-mixed metal phosphate compound. Correspondingly, at least one of MI and MII has more than one oxidation state in the phosphate compound, and more than one oxidation state above the ground state M^0 . The term oxidation state and valence state are used in the art interchangeably.

In another aspect, both MI and MII may have more than one oxidation state and both may be oxidizable from the state initially present in the phosphate compound. Desirably, MII is a metal or semi-metal having a +2 oxidation state, and is selected from Groups 2, 12 and 14 of the Periodic Table. Desirably, MII is selected from non-transition metals and semi-metals. In one embodiment, MII has only one oxidation state and is nonoxidizable from its oxidation state in the lithium-mixed metal compound. In another embodiment, MII has more than one oxidation state. Examples of semi-metals having more than one oxidation state are selenium and tellurium; other non-transition metals with more than one oxidation state are tin and lead. Preferably, MII is selected from Mg (magnesium), Ca (calcium), Zn (zinc), Sr (strontium), Pb (lead), Cd (cadmium), Sn (tin), Ba (barium), and Be (beryllium), and mixtures thereof. In another preferred aspect, MII is a metal having a +2 oxidation state and having more than one oxidation state, and is oxidizable from its oxidation state in lithium-mixed metal compound.

Desirably, MI is selected from Fe (iron), Co (cobalt), Ni (nickel), Mn (manganese), Cu (copper), V (vanadium), Sn (tin), Ti (titanium), Cr (chromium), and

mixtures thereof. As can be seen, MI is preferably selected from the first row of transition metals and further includes tin, and MI preferably initially has a +2 oxidation state.

5 In a preferred aspect, the product $\text{LiMI}_{1-y}\text{MII}_y\text{PO}_4$ is an olivine structure and the product $\text{Li}_3\text{MI}_{1-y}(\text{PO}_4)_3$ is a rhombohedral or monoclinic Nasicon structure. In another aspect, the term "nominal formula" refers to the fact that the relative proportion of atomic species may vary
10 slightly on the order of 2 percent to 5 percent, or more typically, 1 percent to 3 percent. In still another aspect, any portion of P (phosphorous) may be substituted by Si (silicon), S (sulfur), and/or As (arsenic); and any portion of O (oxygen) may be substituted by halogen,
15 preferably F (fluorine). These aspects are also disclosed in U.S. Patent Application Serial Numbers 09/105,748 filed June 26, 1998, and 09/274,371 filed March 23, 1999; and in U.S. Patent No. 5,871,866 issued February 16, 1999, which is incorporated by reference in
20 its entirety; each of the listed applications and patents are co-owned by the assignee of the present invention.

The metal phosphates are alternatively represented by the nominal general formulas such as $\text{Li}_{1-x}\text{MI}_{1-y}\text{MII}_y\text{PO}_4$ ($0 \leq x \leq 1$), and $\text{Li}_{3-x}\text{MI}_{2-y}\text{MII}_y(\text{PO}_4)_3$
25 signifying capability to release and reinsert lithium. The term "general" refers to a family of compounds, with M, x and y representing variations therein. The expressions 2-y and 1-y each signify that the relative amount of MI and MII may vary. In addition, as stated
30 above, MI may be a mixture of metals meeting the earlier stated criteria for MI. In addition, MII may be a mixture of metallic elements meeting the stated criteria

for MII. Preferably, where MII is a mixture, it is a mixture of 2 metallic elements; and where MI is a mixture, it is a mixture of 2 metals. Preferably, each such metal and metallic element has a +2 oxidation state in the initial phosphate compound.

The active material of the counter electrode is any material compatible with the lithium-mixed metal phosphate of the invention. Where the lithium-mixed metal phosphate is used as a positive electrode active material, metallic lithium, lithium-containing material, or non-lithium-containing material may be used as the negative electrode active material. The negative electrode is desirably a nonmetallic insertion material. Desirably, the negative electrode comprises an active material from the group consisting of metal oxide, particularly transition metal oxide, metal chalcogenide, carbon, graphite, and mixtures thereof. It is preferred that the anode active material comprises a carbonaceous material such as graphite. The lithium-mixed metal phosphate of the invention may also be used as a negative electrode material.

In another embodiment, the present invention provides a method of preparing a compound of the nominal general formula $\text{Li}_a\text{MI}_b\text{MII}_c(\text{PO}_4)_d$ where $0 < a \leq 3$; the sum of b plus c is greater than zero and up to about 2; and $0 < d \leq 3$. Preferred compounds include $\text{Li}_3\text{MI}_b\text{MII}_c(\text{PO}_4)_3$ where b plus c is about 2; and $\text{LiMI}_b\text{MII}_c\text{PO}_4$ where b plus c is about 1. The method comprises providing starting materials in particle form. The starting (precursor) materials include a lithium-containing compound, one or more metal containing compounds, a compound capable of providing the phosphate $(\text{PO}_4)^{-3}$ anion, and carbon.

Preferably, the lithium-containing compound is in particle form, and an example is lithium salt.

Preferably, the phosphate-containing anion compound is in particle form, and examples include metal phosphate salt

5 and diammonium hydrogen phosphate (DAHP) and ammonium dihydrogen phosphate (ADHP). The lithium compound, one or more metal compounds, and phosphate compound are included in a proportion which provides the stated nominal general formula. The starting materials are
10 mixed together with carbon, which is included in an amount sufficient to reduce the metal ion of one or more of the metal-containing starting materials without full reduction to an elemental metal state. Excess quantities of carbon and one or more other starting materials (i.e.,
15 5 to 10% excess) may be used to enhance product quality. A small amount of carbon, remaining after the reaction, functions as a conductive constituent in the ultimate electrode formulation. This is an advantage since such remaining carbon is very intimately mixed with the
20 product active material. Accordingly, large quantities of excess carbon, on the order of 100% excess carbon are useable in the process. The carbon present during compound formation is thought to be intimately dispersed throughout the precursor and product. This provides many
25 advantages, including the enhanced conductivity of the product. The presence of carbon particles in the starting materials is also thought to provide nucleation sites for the production of the product crystals.

The starting materials are intimately mixed and
30 then reacted together where the reaction is initiated by heat and is preferably conducted in a nonoxidizing, inert atmosphere, whereby the lithium, metal from the metal compound(s), and phosphate combine to form the

9

00484799-011800

Li₃MI_bMII_c(PO₄)_d product. Before reacting the compounds, the particles are intermingled to form an essentially homogeneous powder mixture of the precursors. In one aspect, the precursor powders are dry-mixed using a ball mill, such as zirconia media. Then the mixed powders are pressed into pellets. In another aspect, the precursor powders are mixed with a binder. The binder is selected so as to not inhibit reaction between particles of the powders. Therefore, preferred binders decompose or evaporate at a temperature less than the reaction temperature. Examples include mineral oils (i.e., glycerol, or C-18 hydrocarbon mineral oil) and polymers which decompose (carbonize) to form a carbon residue before the reaction starts, or which evaporate before the reaction starts. In still another aspect, intermingling is conducted by forming a wet mixture using a volatile solvent and then the intermingled particles are pressed together in pellet form to provide good grain-to-grain contact.

Although it is desired that the precursor compounds be present in a proportion which provides the stated general formula of the product, the lithium compound may be present in an excess amount on the order of 5 percent excess lithium compared to a stoichiometric mixture of the precursors. And the carbon may be present at up to 100% excess compared to the stoichiometric amount. The method of the invention may also be used to prepare other novel products, and to prepare known products. A number of lithium compounds are available as precursors, such as lithium acetate (LiOOCCH₃), lithium hydroxide, lithium nitrate (LiNO₃), lithium oxalate (Li₂C₂O₄), lithium oxide (Li₂O), lithium phosphate (Li₃PO₄), lithium dihydrogen phosphate (LiH₂PO₄), lithium

10

vanadate (LiVO_3), and lithium carbonate (Li_2CO_3). The lithium carbonate is preferred for the solid state reaction since it has a very high melting point and commonly reacts with the other precursors before melting. Lithium carbonate has a melting point over 600°C and it decomposes in the presence of the other precursors and/or effectively reacts with the other precursors before melting. In contrast, lithium hydroxide melts at about 400°C . At some reaction temperatures preferred herein of over 450°C the lithium hydroxide will melt before any significant reaction with the other precursors occurs to an effective extent. This melting renders the reaction very difficult to control. In addition, anhydrous LiOH is highly hygroscopic and a significant quantity of water is released during the reaction. Such water needs to be removed from the oven and the resultant product may need to be dried. In one preferred aspect, the solid state reaction made possible by the present invention is much preferred since it is conducted at temperatures at which the lithium-containing compound reacts with the other reactants before melting. Therefore, lithium hydroxide is useable as a precursor in the method of the invention in combination with some precursors, particularly the phosphates. The method of the invention is able to be conducted as an economical carbothermal-based process with a wide variety of precursors and over a relatively broad temperature range.

The aforesaid precursor compounds (starting materials) are generally crystals, granules, and powders and are generally referred to as being in particle form. Although many types of phosphate salts are known, it is preferred to use diammonium hydrogen phosphate $(\text{NH}_4)_2\text{HPO}_4$ (DAHP) or ammonium dihydrogen phosphate $(\text{NH}_4)\text{H}_2\text{PO}_4$ (ADHP).

((

Both ADHP and DAHP meet the preferred criteria that the precursors decompose in the presence of one another or react with one another before melting of such precursor. Exemplary metal compounds are Fe_2O_3 , Fe_3O_4 , V_2O_5 , VO_2 , LiVO_3 , NH_4VO_3 , $\text{Mg}(\text{OH})_2$, CaO , MgO , $\text{Ca}(\text{OH})_2$, MnO_2 , Mn_2O_3 , $\text{Mn}_3(\text{PO}_4)_2$, CuO , SnO , SnO_2 , TiO_2 , Ti_2O_3 , Cr_2O_3 , PbO_2 , PbO , $\text{Ba}(\text{OH})_2$, BaO , $\text{Cd}(\text{OH})_2$. In addition, some starting materials serve as both the source of metal ion and phosphate, such as FePO_4 , $\text{Fe}_3(\text{PO}_4)_2$, $\text{Zn}_3(\text{PO}_4)_2$, and $\text{Mg}_3(\text{PO}_4)_2$. Still others contain both lithium ion and phosphate such as Li_3PO_4 and LiH_2PO_4 . Other exemplary precursors are H_3PO_4 (phosphoric acid); and P_2O_5 (P_4O_{10}) phosphoric oxide; and HPO_3 meta phosphoric acid, which is a decomposition product of P_2O_5 . If it is desired to replace any of the oxygen with a halogen, such as fluorine, the starting materials further include a fluorine compound such as LiF . If it is desired to replace any of the phosphorous with silicon, then the starting materials further include silicon oxide (SiO_2). Similarly, ammonium sulfate in the starting materials is useable to replace phosphorus with sulfur.

The starting materials are available from a number of sources. The following are typical. Vanadium pentoxide of the formula V_2O_5 is obtainable from any number of suppliers including Kerr McGee, Johnson Matthey, or Alpha Products of Davers, Massachusetts. Vanadium pentoxide has a CAS number of 1314-62-1. Iron oxide Fe_3O_3 is a common and very inexpensive material available in powder form from the same suppliers. The other precursor materials mentioned above are also available from well known suppliers, such as those listed above.

00870" 66248460

The method of the invention may also be used to react starting materials in the presence of carbon to form a variety of other novel products, such as gamma-LiV₂O₅ and also to produce known products. Here, the carbon functions to reduce metal ion of a starting metal compound to provide a product containing such reduced metal ion. The method is particularly useful to also add lithium to the resultant product, which thus contains the metallic element ions, namely, the lithium ion and the other metal ion, thereby forming a mixed metal product. An example is the reaction of vanadium pentoxide (V₂O₅) with lithium carbonate in the presence of carbon to form gamma-LiV₂O₅. Here the starting metal ion V⁺⁵V⁺⁵ is reduced to V⁺⁴V⁺⁵ in the final product. A single phase gamma-LiV₂O₅ product is not known to have been directly and independently formed before.

As described earlier, it is desirable to conduct the reaction at a temperature where the lithium compound reacts before melting. The temperature should be about 400°C or greater, and desirably 450°C or greater, and preferably 500°C or greater, and generally will proceed at a faster rate at higher temperatures. The various reactions involve production of CO or CO₂ as an effluent gas. The equilibrium at higher temperature favors CO formation. Some of the reactions are more desirably conducted at temperatures greater than 600°C; most desirably greater than 650°C; preferably 700°C or greater; more preferably 750°C or greater. Suitable ranges for many reactions are about 700 to 950°C, or about 700 to 800°C.

Generally, the higher temperature reactions produce CO effluent and the stoichiometry requires more

13

carbon be used than the case where CO₂ effluent is produced at lower temperature. This is because the reducing effect of the C to CO₂ reaction is greater than the C to CO reaction. The C to CO₂ reaction involves an increase in carbon oxidation state of +4 (from 0 to 4) and the C to CO reaction involves an increase in carbon oxidation state of +2 (from ground state zero to 2). Here, higher temperature generally refers to a range of about 650°C to about 1000°C and lower temperature refers to up to about 650°C. Temperatures higher than 1200°C are not thought to be needed.

In one aspect, the method of the invention utilizes the reducing capabilities of carbon in a unique and controlled manner to produce desired products having structure and lithium content suitable for electrode active materials. The method of the invention makes it possible to produce products containing lithium, metal and oxygen in an economical and convenient process. The ability to lithiate precursors, and change the oxidation state of a metal without causing abstraction of oxygen from a precursor is heretofore unexpected. These advantages are at least in part achieved by the reductant, carbon, having an oxide whose free energy of formation becomes more negative as temperature increases. Such oxide of carbon is more stable at high temperature than at low temperature. This feature is used to produce products having one or more metal ions in a reduced oxidation state relative to the precursor metal ion oxidation state. The method utilizes an effective combination of quantity of carbon, time and temperature to produce new products and to produce known products in a new way.

Referring back to the discussion of temperature, at about 700°C both the carbon to carbon monoxide and the carbon to carbon dioxide reactions are occurring. At closer to 600°C the C to CO₂ reaction is the dominant reaction. At closer to 800°C the C to CO reaction is dominant. Since the reducing effect of the C to CO₂ reaction is greater, the result is that less carbon is needed per atomic unit of metal to be reduced. In the case of carbon to carbon monoxide, each atomic unit of carbon is oxidized from ground state zero to plus 2. Thus, for each atomic unit of metal ion (M) which is being reduced by one oxidation state, one half atomic unit of carbon is required. In the case of the carbon to carbon dioxide reaction, one quarter atomic unit of carbon is stoichiometrically required for each atomic unit of metal ion (M) which is reduced by one oxidation state, because carbon goes from ground state zero to a plus 4 oxidation state. These same relationships apply for each such metal ion being reduced and for each unit reduction in oxidation state desired.

It is preferred to heat the starting materials at a ramp rate of a fraction of a degree to 10°C per minute and preferably about 2°C per minute. Once the desired reaction temperature is attained, the reactants (starting materials) are held at the reaction temperature for several hours. The heating is preferably conducted under non-oxidizing or inert gas such as argon or vacuum. Advantageously, a reducing atmosphere is not required, although it may be used if desired. After reaction, the products are preferably cooled from the elevated temperature to ambient (room) temperature (i.e., 10°C to 40°C). Desirably, the cooling occurs at a rate similar to the earlier ramp rate, and preferably 2°C/minute

15

cooling. Such cooling rate has been found to be adequate to achieve the desired structure of the final product. It is also possible to quench the products at a cooling rate on the order of about 100°C/minute. In some instances, such rapid cooling (quench) may be preferred.

The present invention resolves the capacity problem posed by widely used cathode active material. It has been found that the capacity and capacity retention of cells having the preferred active material of the invention are improved over conventional materials. Optimized cells containing lithium-mixed metal phosphates of the invention potentially have performance improved over commonly used lithium metal oxide compounds. Advantageously, the new method of making the novel lithium-mixed metal phosphate compounds of the invention is relatively economical and readily adaptable to commercial production.

Objects, features, and advantages of the invention include an electrochemical cell or battery based on lithium-mixed metal phosphates. Another object is to provide an electrode active material which combines the advantages of good discharge capacity and capacity retention. It is also an object of the present invention to provide electrodes which can be manufactured economically. Another object is to provide a method for forming electrode active material which lends itself to commercial scale production for preparation of large quantities.

16

These and other objects, features, and advantages will become apparent from the following description of the preferred embodiments, claims, and accompanying drawings.

09464799-011800

Brief Description of the Drawings

Figure 1 shows the results of an x-ray diffraction analysis, of the LiFePO_4 prepared according to the invention using $\text{CuK}\alpha$ radiation, $\lambda = 1.5405\text{\AA}$. Bars refer to simulated pattern from refined cell parameters, Space Group, SG = Pnma (62). The values are $a = 10.2883\text{\AA}$ (0.0020), $b = 5.9759\text{\AA}$ (0.0037), $c = 4.6717\text{\AA}$ (0.0012) 0.0072, cell volume = 287.2264\AA^3 (0.0685). Density, $\rho = 3.605$ g/cc, zero = 0.452 (0.003). Peak at full width half maximum, PFWHM = 0.21. Crystallite size from XRD data = 704\AA .

Figure 2 is a voltage/capacity plot of LiFePO_4 -containing cathode cycled with a lithium metal anode using constant current cycling at ± 0.2 milliamps per square centimeter in a range of 2.5 to 4.0 volts at a temperature of about 23°C . The cathode contained 19.0mg of the LiFePO_4 active material, prepared by the method of the invention. The electrolyte comprised ethylene carbonate (EC) and dimethyl carbonate (DMC) in a weight ratio of 2:1 and included a 1 molar concentration of LiPF_6 salt. The lithium-metal-phosphate containing electrode and the lithium metal counter electrode are maintained spaced apart by a glass fiber separator which is interpenetrated by the solvent and the salt.

Figure 3 shows multiple constant current cycling of LiFePO_4 active material cycled with a lithium metal anode using the electrolyte as described in connection with **Figure 2** and cycled, charge and discharge at ± 0.2 milliamps per square centimeter, 2.5 to 4.0 volts at two different temperature conditions, 23°C and 60°C . **Figure 3** shows the excellent rechargeability of

the lithium iron phosphate/lithium metal cell, and also shows the excellent cycling and specific capacity (mAh/g) of the active material.

Figure 4 shows the results of an x-ray diffraction analysis, of the $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ prepared according to the invention, using $\text{CuK}\alpha$ radiation, $\lambda = 1.5405\text{\AA}$. Bars refer to simulated pattern from refined cell parameters SG = Pnma (62). The values are $a = 10.2688\text{\AA}$ (0.0069), $b = 5.9709\text{\AA}$ (0.0072), $c = 4.6762\text{\AA}$ (0.0054), cell volume = 286.7208\AA^3 (0.04294), $\rho = 3.617$ g/cc, zero = 0.702 (0.003), PFWHM = 0.01, and crystallite = 950\AA .

Figure 5 is a voltage/capacity plot of $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ -containing cathode cycled with a lithium metal anode using constant current cycling at ± 0.2 milliamps per square centimeter in a range of 2.5 to 4.0 volts. Other conditions are as described earlier with respect to **Figure 2**. The cathode contained 18.9mg of the $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ active material prepared by the method of the invention.

Figure 6 shows multiple constant current cycling of $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ cycled with a lithium metal anode using the electrolyte as described in connection with **Figure 2** and cycled, charge and discharge at ± 0.2 milliamps per square centimeter, 2.5 to 4.0 volts at two different temperature conditions, 23°C and 60°C . **Figure 6** shows the excellent rechargeability of the lithium-metal-phosphate/lithium metal cell, and also shows the excellent cycling and capacity of the cell.

Figure 7 is a voltage/capacity plot of $\text{LiFe}_{0.8}\text{Mg}_{0.2}\text{PO}_4$ -containing cathode cycled with a lithium metal anode using constant current cycling at ± 0.2 milliamps per square centimeter in a range of 2.5 to 4.0 volts at 23°C . Other conditions are as described earlier with respect to **Figure 2**. The cathode contained 16mg of the $\text{LiFe}_{0.8}\text{Mg}_{0.2}\text{PO}_4$ active material prepared by the method of the invention.

Figure 8 shows the results of an x-ray diffraction analysis, of the $\text{LiFe}_{0.9}\text{Ca}_{0.1}\text{PO}_4$ prepared according to the invention, using $\text{CuK}\alpha$ radiation, $\lambda = 1.5405\text{\AA}$. Bars refer to simulated pattern from refined cell parameters SG = Pnma (62). The values are $a = 10.3240\text{\AA}$ (0.0045), $b = 6.0042\text{\AA}$ (0.0031), $c = 4.6887\text{\AA}$ (0.0020), cell volume = 290.6370\AA^3 (0.1807), zero = 0.702 (0.003), $\rho = 3.62$ g/cc, PFWHM = 0.18, and crystallite = 680\AA .

Figure 9 is a voltage/capacity plot of $\text{LiFe}_{0.8}\text{Ca}_{0.2}\text{PO}_4$ -containing cathode cycled with a lithium metal anode using constant current cycling at ± 0.2 milliamps per square centimeter in a range of 2.5 to 4.0 volts at 23° . Other conditions are as described earlier with respect to **Figure 2**. The cathode contained 18.5mg of the $\text{LiFe}_{0.8}\text{Ca}_{0.2}\text{PO}_4$ active material prepared by the method of the invention.

Figure 10 is a voltage/capacity plot of $\text{LiFe}_{0.8}\text{Zn}_{0.2}\text{PO}_4$ -containing cathode cycled with a lithium metal anode using constant current cycling at ± 0.2 milliamps per square centimeter in a range of 2.5 to 4.0 volts at 23°C . Other conditions are as described earlier with respect to **Figure 2**. The cathode contained 18.9mg

20

of the $\text{LiFe}_{0.8}\text{Zn}_{0.2}\text{PO}_4$ active material prepared by the method of the invention.

Figure 11 shows the results of an x-ray diffraction analysis of the gamma- $\text{Li}_x\text{V}_2\text{O}_5$ ($x = 1$, gamma LiV_2O_5) prepared according to the invention using $\text{CuK}\alpha$ radiation $\lambda = 1.5405\text{\AA}$. The values are $a = 9.687\text{\AA}$ (1), $b = 3.603\text{\AA}$ (2), and $c = 10.677\text{\AA}$ (3); phase type is gamma- $\text{Li}_x\text{V}_2\text{O}_5$ ($x = 1$); symmetry is orthorhombic; and space group is Pnma.

Figure 12 is a voltage/capacity plot of gamma- LiV_2O_5 -containing cathode cycled with a lithium metal anode using constant current cycling at ± 0.2 milliamps per square centimeter in a range of 2.5 to 3.8 volts at 23°C . Other conditions are as described earlier with respect to **Figure 2**. The cathode contained 21mg of the gamma- LiV_2O_5 active material prepared by the method of the invention.

Figure 13 is a two-part graph based on multiple constant current cycling of gamma- LiV_2O_5 cycled with a lithium metal anode using the electrolyte as described in connection with **Figure 2** and cycled, charge and discharge at ± 0.2 milliamps per square centimeter, 2.5 to 3.8 volts. In the two-part graph, **Figure 13** shows the excellent rechargeability of the lithium-metal-oxide/lithium metal cell. **Figure 13** shows the excellent cycling and capacity of the cell.

Figure 14 shows the results of an x-ray diffraction analysis of the $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ prepared according to the invention. The analysis is based on $\text{CuK}\alpha$

radiation, $\lambda = 1.5405\text{\AA}$. The values are $a = 12.184\text{\AA}$ (2), $b = 8.679\text{\AA}$ (2), $c = 8.627\text{\AA}$ (3), and $\beta = 90.457^\circ$ (4).

Figure 15 shows the results of an x-ray diffraction analysis of $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ prepared according to a method described in U.S. Patent No. 5,871,866. The analysis is based on $\text{CuK}\alpha$ radiation, $\lambda = 1.5405\text{\AA}$. The values are $a = 12.155\text{\AA}$ (2), $b = 8.711\text{\AA}$ (2), $c = 8.645\text{\AA}$ (3); the angle beta is 90.175° (6); symmetry is Monoclinic; and space group is $P2_1/n$.

Figure 16 is an EVS (Electrochemical Voltage Spectroscopy) voltage/capacity profile for a cell with cathode material formed by the carbothermal reduction method of the invention. The cathode material is 13.8mg of $\text{Li}_3\text{V}_2(\text{PO}_4)_3$. The cell includes a lithium metal counter electrode in an electrolyte comprising ethylene carbonate (EC) and dimethyl carbonate (DMC) in a weight ratio of 2:1 and including a 1 molar concentration of LiPF_6 salt. The lithium-metal-phosphate containing electrode and the lithium metal counter electrode are maintained spaced apart by a fiberglass separator which is interpenetrated by the solvent and the salt. The conditions are ± 10 mV steps, between about 3.0 and 4.2 volts, and the critical limiting current density is less than or equal to 0.1 mA/cm^2 .

Figure 17 is an EVS differential capacity versus voltage plot for the cell as described in connection with **Figure 16**.

Figure 18 shows multiple constant current cycling of $\text{LiFe}_{0.8}\text{Mg}_{0.2}\text{PO}_4$ cycled with a lithium metal anode using the electrolyte as described in connection

22

with **Figure 2** and cycled, charge and discharge at ± 0.2 milliamps per square centimeter, 2.5 to 4.0 volts at two different temperature conditions, 23°C and 60°C. **Figure 18** shows the excellent rechargeability of the lithium-metal-phosphate/lithium metal cell, and also shows the excellent cycling and capacity of the cell.

Figure 19 is a graph of potential over time for the first four complete cycles of the $\text{LiMg}_{0.1}\text{Fe}_{0.9}\text{PO}_4/\text{MCMB}$ graphite cell of the invention.

Figure 20 is a two-part graph based on multiple constant current cycling of $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ cycled with an MCMB graphite anode using the electrolyte as described in connection with **Figure 2** and cycled, charge and discharge at ± 0.2 milliamps per square centimeter, 2.5 to 3.6 volts, 23°C and based on a C/10 (10 hour) rate. In the two-part graph, **Figure 20** shows the excellent rechargeability of the lithium-metal-phosphate/graphite cell. **Figure 20** shows the excellent cycling and capacity of the cell.

Figure 21 is a graph of potential over time for the first three complete cycles of the $\gamma\text{-LiV}_2\text{O}_5/\text{MCMB}$ graphite cell of the invention.

Figure 22 is a diagrammatic representation of a typical laminated lithium-ion battery cell structure.

Figure 23 is a diagrammatic representation of a typical multi-cell battery cell structure.

Detailed Description of the Preferred Embodiments

The present invention provides lithium-mixed metal-phosphates, which are usable as electrode active materials, for lithium (Li^+) ion removal and insertion.

5 Upon extraction of the lithium ions from the lithium-mixed-metal-phosphates, significant capacity is achieved. In one aspect of the invention, electrochemical energy is provided when combined with a suitable counter electrode by extraction of a quantity x of lithium from lithium-mixed-metal-phosphates $\text{Li}_{a-x}\text{MI}_b\text{MII}_c(\text{PO}_4)_d$. When a quantity x of lithium is removed per formula unit of the lithium-mixed-metal phosphate, metal MI is oxidized. In another aspect, metal MII is also oxidized. Therefore, at least one of MI and MII is oxidizable from its initial
10 condition in the phosphate compound as Li is removed. Consider the following which illustrate the mixed metal compounds of the invention: $\text{LiFe}_{1-y}\text{Sn}_y\text{PO}_4$, has two oxidizable elements, Fe and Sn; in contrast, $\text{LiFe}_{1-y}\text{Mg}_y\text{PO}_4$ has one oxidizable metal, the metal Fe.
15

20 In another aspect, the invention provides a lithium ion battery which comprises an electrolyte; a negative electrode having an insertion active material; and a positive electrode comprising a lithium-mixed-metal-phosphate active material characterized by an
25 ability to release lithium ions for insertion into the negative electrode active material. The lithium-mixed-metal-phosphate is desirably represented by the nominal general formula $\text{Li}_a\text{MI}_b\text{MII}_c(\text{PO}_4)_d$. Although the metals MI and MII may be the same, it is preferred that the metals
30 MI and MII are different. Desirably, in the phosphate compound MI is a metal selected from the group: Fe, Co, Ni, Mn, Cu, V, Sn, Ti, Cr and mixtures thereof, and MI is

most desirably a transition metal or mixture thereof selected from said group. Most preferably, MI has a +2 valence or oxidation state.

In another aspect, MII is selected from Mg, Ca, Zn, Sr, Pb, Cd, Sn, Ba, Be, and mixtures thereof. Most preferably, MII has a +2 valence or oxidation state. The lithium-mixed-metal-phosphate is preferably a compound represented by the nominal general formula $\text{Li}_{a-x}\text{MI}_b\text{MII}_c(\text{PO}_4)_d$, signifying the preferred composition and its capability to release x lithium. Accordingly, during cycling, charge and discharge, the value of x varies as x greater than or equal to 0 and less than or equal to a. The present invention resolves a capacity problem posed by conventional cathode active materials. Such problems with conventional active materials are described by Tarascon in U.S. Patent No. 5,425,932, using LiMn_2O_4 as an example. Similar problems are observed with LiCoO_2 , LiNiO_2 , and many, if not all, lithium metal chalcogenide materials. The present invention demonstrates that significant capacity of the cathode active material is utilizable and maintained.

A preferred novel procedure for forming the lithium-mixed-metal-phosphate $\text{Li}_a\text{MI}_b\text{MII}_c(\text{PO}_4)_d$ compound active material will now be described. In addition, the preferred novel procedure is also applicable to formation of other lithium metal compounds, and will be described as such. The basic procedure will be described with reference to exemplary starting materials but is not limited thereby. The basic process comprises conducting a reaction between a lithium compound, preferably lithium carbonate (Li_2CO_3), metal compound(s), for example, vanadium pentoxide (V_2O_5), iron oxide (Fe_2O_3), and/or

25

manganese hydroxide, and a phosphoric acid derivative, preferably the phosphoric acid ammonium salt, diammonium hydrogen phosphate, $(\text{NH}_4)_2\text{H}(\text{PO}_4)$. Each of the precursor starting materials are available from a number of chemical outfits including Aldrich Chemical Company and Fluka. Using the method described herein, LiFePO_4 and $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$, $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ were prepared with approximately a stoichiometric amount of Li_2CO_3 , the respective metal compound, and $(\text{NH}_4)_2\text{HPO}_4$. Carbon powder was included with these precursor materials. The precursor materials were initially intimately mixed and dry ground for about 30 minutes. The intimately mixed compounds were then pressed into pellets. Reaction was conducted by heating in an oven at a preferred ramped heating rate to an elevated temperature, and held at such elevated temperature for several hours to complete formation of the reaction product. The entire reaction was conducted in a non-oxidizing atmosphere, under flowing pure argon gas. The flow rate will depend upon the size of the oven and the quantity needed to maintain the atmosphere. The oven was permitted to cool down at the end of the reaction period, where cooling occurred at a desired rate under argon. Exemplary and preferred ramp rates, elevated reaction temperatures and reaction times are described herein. In one aspect, a ramp rate of $2^\circ/\text{minute}$ to an elevated temperature in a range of 750°C to 800°C was suitable along with a dwell (reaction time) of 8 hours. Refer to Reactions 1, 2, 3 and 4 herein. In another variation per Reaction 5, a reaction temperature of 600°C was used along with a dwell time of about one hour. In still another variation, as per Reaction 6, a two-stage heating was conducted, first to a temperature of 300°C and then to a temperature of 850° .

fabricated using lithium metal electrodes. When forming cells for use as batteries, it is preferred to use an insertion positive electrode as per the invention and a graphitic carbon negative electrode.

5 A typical laminated battery cell structure 10 is depicted in **Figure 22**. It comprises a negative electrode side 12, a positive electrode side 14, and an electrolyte/separator 16 there between. Negative electrode side 12 includes current collector 18, and positive electrode side 14 includes current collector 22. A copper collector foil 18, preferably in the form of an open mesh grid, upon which is laid a negative electrode membrane 20 comprising an insertion material such as carbon or graphite or low-voltage lithium insertion compound, dispersed in a polymeric binder matrix. An electrolyte/separator film 16 membrane is preferably a plasticized copolymer. This electrolyte/separator preferably comprises a polymeric separator and a suitable electrolyte for ion transport. The electrolyte/separator is positioned upon the electrode element and is covered with a positive electrode membrane 24 comprising a composition of a finely divided lithium insertion compound in a polymeric binder matrix. An aluminum collector foil or grid 22 completes the assembly. Protective bagging material 40 covers the cell and prevents infiltration of air and moisture.

In another embodiment, a multi-cell battery configuration as per **Figure 23** is prepared with copper current collector 51, negative electrode 53, electrolyte/separator 55, positive electrode 57, and aluminum current collector 59. Tabs 52 and 58 of the current collector elements form respective terminals for

the battery structure. As used herein, the terms "cell" and "battery" refer to an individual cell comprising anode/electrolyte/cathode and also refer to a multi-cell arrangement in a stack.

5 The relative weight proportions of the components of the positive electrode are generally: 50-90% by weight active material; 5-30% carbon black as the electric conductive diluent; and 3-20% binder chosen to hold all particulate materials in contact with one
10 another without degrading ionic conductivity. Stated ranges are not critical, and the amount of active material in an electrode may range from 25-95 weight percent. The negative electrode comprises about 50-95% by weight of a preferred graphite, with the balance
15 constituted by the binder. A typical electrolyte separator film comprises approximately two parts polymer for every one part of a preferred fumed silica. The conductive solvent comprises any number of suitable solvents and salts. Desirable solvents and salts are
20 described in U.S. Patent Nos. 5,643,695 and 5,418,091. One example is a mixture of EC:DMC:LiPF₆ in a weight ratio of about 60:30:10.

Solvents are selected to be used individually or in mixtures, and include dimethyl carbonate (DMC),
25 diethylcarbonate (DEC), dipropylcarbonate (DPC), ethylmethylcarbonate (EMC), ethylene carbonate (EC), propylene carbonate (PC), butylene carbonate, lactones, esters, glymes, sulfoxides, sulfolanes, etc. The preferred solvents are EC/DMC, EC/DEC, EC/DPC and EC/EMC.
30 The salt content ranges from 5% to 65% by weight, preferably from 8% to 35% by weight.

Those skilled in the art will understand that any number of methods are used to form films from the casting solution using conventional meter bar or doctor blade apparatus. It is usually sufficient to air-dry the films at moderate temperature to yield self-supporting films of copolymer composition. Lamination of assembled cell structures is accomplished by conventional means by pressing between metal plates at a temperature of about 120-160°C. Subsequent to lamination, the battery cell material may be stored either with the retained plasticizer or as a dry sheet after extraction of the plasticizer with a selective low-boiling point solvent. The plasticizer extraction solvent is not critical, and methanol or ether are often used.

Separator membrane element 16 is generally polymeric and prepared from a composition comprising a copolymer. A preferred composition is the 75 to 92% vinylidene fluoride with 8 to 25% hexafluoropropylene copolymer (available commercially from Atochem North America as Kynar FLEX) and an organic solvent plasticizer. Such a copolymer composition is also preferred for the preparation of the electrode membrane elements, since subsequent laminate interface compatibility is ensured. The plasticizing solvent may be one of the various organic compounds commonly used as solvents for electrolyte salts, e.g., propylene carbonate or ethylene carbonate, as well as mixtures of these compounds. Higher-boiling plasticizer compounds such as dibutyl phthalate, dimethyl phthalate, diethyl phthalate, and tris butoxyethyl phosphate are particularly suitable. Inorganic filler adjuncts, such as fumed alumina or silanized fumed silica, may be used to enhance the physical strength and melt viscosity of a separator

membrane and, in some compositions, to increase the subsequent level of electrolyte solution absorption.

09434799-011300

In the construction of a lithium-ion battery, a current collector layer of aluminum foil or grid is overlaid with a positive electrode film, or membrane, separately prepared as a coated layer of a dispersion of insertion electrode composition. This is typically an insertion compound such as LiMn_2O_4 (LMO), LiCoO_2 , or LiNiO_2 , powder in a copolymer matrix solution, which is dried to form the positive electrode. An electrolyte/separator membrane is formed as a dried coating of a composition comprising a solution containing VdF:HFP copolymer and a plasticizer solvent is then overlaid on the positive electrode film. A negative electrode membrane formed as a dried coating of a powdered carbon or other negative electrode material dispersion in a VdF:HFP copolymer matrix solution is similarly overlaid on the separator membrane layer. A copper current collector foil or grid is laid upon the negative electrode layer to complete the cell assembly. Therefore, the VdF:HFP copolymer composition is used as a binder in all of the major cell components, positive electrode film, negative electrode film, and electrolyte/separator membrane. The assembled components are then heated under pressure to achieve heat-fusion bonding between the plasticized copolymer matrix electrode and electrolyte components, and to the collector grids, to thereby form an effective laminate of cell elements. This produces an essentially unitary and flexible battery cell structure.

Examples of forming cells containing metallic lithium anode, insertion electrodes, solid electrolytes

131

and liquid electrolytes can be found in U.S. Patent Nos. 4,668,595; 4,830,939; 4,935,317; 4,990,413; 4,792,504; 5,037,712; 5,262,253; 5,300,373; 5,435,054; 5,463,179; 5,399,447; 5,482,795 and 5,411,820; each of which is
5 incorporated herein by reference in its entirety. Note that the older generation of cells contained organic polymeric and inorganic electrolyte matrix materials, with the polymeric being most preferred. The polyethylene oxide of 5,411,820 is an example. More
10 modern examples are the VdF:HFP polymeric matrix. Examples of casting, lamination and formation of cells using VdF:HFP are as described in U.S. Patent Nos. 5,418,091; 5,460,904; 5,456,000; and 5,540,741; assigned to Bell Communications Research, each of which is
15 incorporated herein by reference in its entirety.

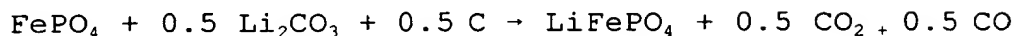
As described earlier, the electrochemical cell operated as per the invention, may be prepared in a variety of ways. In one embodiment, the negative electrode may be metallic lithium. In more desirable
20 embodiments, the negative electrode is an insertion active material, such as, metal oxides and graphite. When a metal oxide active material is used, the components of the electrode are the metal oxide, electrically conductive carbon, and binder, in
25 proportions similar to that described above for the positive electrode. In a preferred embodiment, the negative electrode active material is graphite particles. For test purposes, test cells are often fabricated using lithium metal electrodes. When forming cells for use as
30 batteries, it is preferred to use an insertion metal oxide positive electrode and a graphitic carbon negative electrode. Various methods for fabricating electrochemical cells and batteries and for forming

electrode components are described herein. The invention is not, however, limited by any particular fabrication method.

00370" 65248460

Formation of Active Materials**EXAMPLE I**

Reaction 1(a). LiFePO_4 formed from FePO_4



- 5 (a) Pre-mix reactants in the following proportions using ball mill. Thus,

1 mol FePO_4	150.82g
0.5 mol Li_2CO_3	36.95g
0.5 mol carbon	6.0g

10

(but use 100% excess carbon \rightarrow 12.00g)

- (b) Pelletize powder mixture
- (c) Heat pellet to 750°C at a rate of $2^\circ/\text{minute}$ in flowing inert atmosphere (e.g. argon). Dwell for 8 hours at 750°C under argon.

15

- (d) Cool to room temperature at $2^\circ/\text{minute}$ under argon.

Powderize pellet.

It is noted that at 750°C this is predominantly a CO reaction. This reaction is able to be carried out at a temperature in a range of about 750°C to about 950°C in argon as shown, and in other inert atmospheres such as vacuum.

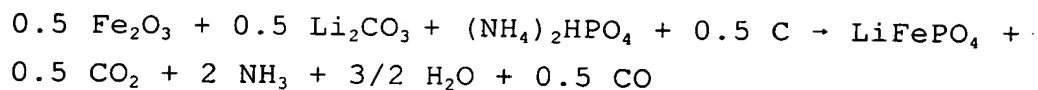
34

09434799-011300

1,340

EXAMPLE II

Reaction 1(b). LiFePO_4 formed from Fe_2O_3



- 5 (a) Premix powders in the following proportions

0.5 mol Fe_2O_3	79.85g
0.5 mol Li_2CO_3	36.95g
1 mol $(\text{NH}_4)_2\text{HPO}_4$	132.06g
0.5 mol carbon	6.00g

- 10 (use 100% excess carbon \rightarrow 12.00g)

- (b) Pelletize powder mixture

- (c) Heat pellet to 750°C at a rate of $2^\circ/\text{minute}$ in flowing inert atmosphere (e.g. argon). Dwell for 8 hours at 750°C under argon.

- 15 (d) Cool to room temperature at $2^\circ/\text{minute}$ under argon.

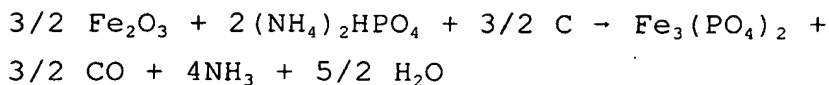
- (e) Powderize

EXAMPLE III

Reaction 1(c). LiFePO_4 - from $\text{Fe}_3(\text{PO}_4)_2$

- 20 Two steps:

35

Part I. Carbothermal preparation of $\text{Fe}_3(\text{PO}_4)_2$ 

(a) Premix reactants in the following proportions

3/2 mol Fe_2O_3 239.54g2 mol $(\text{NH}_4)_2\text{HPO}_4$ 264.12g

3/2 mol carbon 18.00g

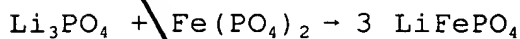
(use 100% excess carbon - 36.00g)

(b) Pelletize powder mixture

(c) Heat pellet to 800°C at a rate of 2°/minute in flowing inert atmosphere (e.g. argon). Dwell for 8 hours at 750°C under argon.

(d) Cool to room temperature at 2°C/minute under argon.

(e) Powderize pellet.

Part II. Preparation of LiFePO_4 from the $\text{Fe}_3(\text{PO}_4)_2$ of Part I.

(a) Premix reactants in the following proportions

1 mol Li_3PO_4 115.79g1 mol $\text{Fe}_3(\text{PO}_4)_2$ 357.48g

(b) Pelletize powder mixture

36

(c) Heat pellet to 750°C at a rate of 2°/minute in flowing inert atmosphere (e.g. argon). Dwell for 8 hours at 750°C under argon.

5

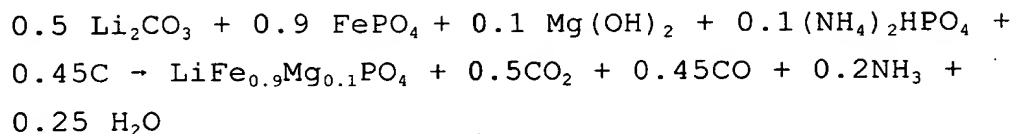
(d) Cool to room temperature at 2°C/minute under argon.

(e) Powderize pellet.

EXAMPLE IV

Reaction 2(a). $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ ($\text{LiFe}_{1-y}\text{Mg}_y\text{PO}_4$) formed from FePO_4

10



(a) Pre-mix reactants in the following proportions

15

0.50 mol Li_2CO_3	=	36.95g
0.90 mol FePO_4	=	135.74g
0.10 mol Mg(OH)_2	=	5.83g
0.10 mol $(\text{NH}_4)_2\text{HPO}_4$	=	1.32g
0.45 mol carbon	=	5.40g

(use 100% excess carbon - 10.80g)

20

(b) Pelletize powder mixture

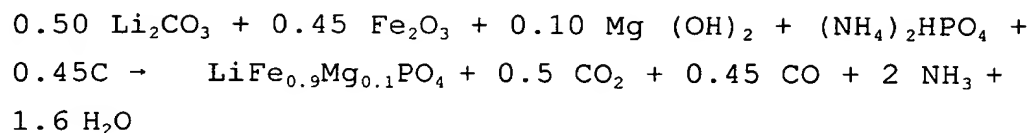
(c) Heat to 750°C at a rate of 2°/minute in argon. Hold for 8 hours dwell at 750°C in argon

(d) Cool at a rate of 2°/minute

(e) Powderize pellet.

EXAMPLE V

5 Reaction 2(b). $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ ($\text{LiFe}_{1-y}\text{Mg}_y\text{PO}_4$) formed from Fe_2O_3



10

(a) Pre-mix reactants in following ratio

0.50 mol Li_2CO_3	=	36.95g
0.45 mol Fe_2O_3	=	71.86g
0.10 mol Mg (OH)_2	=	5.83g
1.00 mol $(\text{NH}_4)_2\text{HPO}_4$	=	132.06g
0.45 mol carbon	=	5.40g

15

(use 100% excess carbon \rightarrow 10.80g)

(b) Pelletize powder mixture

(c) Heat to 750°C at a rate of $2^\circ/\text{minute}$ in argon.
Hold for 8 hours dwell at 750°C in argon

20

(d) Cool at a rate of $2^\circ/\text{minute}$

(e) Powderize pellet.

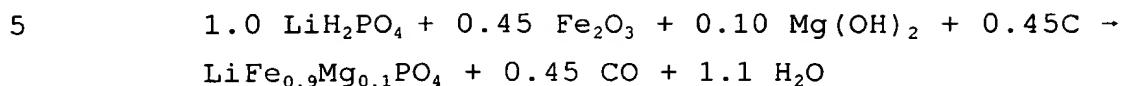
00370 65248468

038d

38

EXAMPLE VI

Reaction 2(c). $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ ($\text{LiFe}_{1-y}\text{Mg}_y\text{PO}_4$) formed from LiH_2PO_4



(a) Pre-mix reactants in the following proportions

1.00 mol LiH_2PO_4	=	103.93g
0.45 mol Fe_2O_3	=	71.86g
0.10 mol Mg(OH)_2	=	5.83g
0.45 mol carbon	=	5.40g

(use 100% excess carbon \rightarrow 10.80g)

(b) Pelletize powder mixture

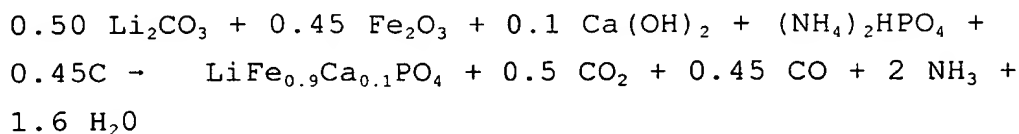
15 (c) Heat to 750°C at a rate of $2^\circ/\text{minute}$ in argon.
 Hold for 8 hours dwell at 750°C in argon

(d) Cool at a rate of $2^\circ/\text{minute}$

(e) Powderize pellet.

EXAMPLE VII

20 Reaction 3. Formation of $\text{LiFe}_{0.9}\text{Ca}_{0.1}\text{PO}_4$
 ($\text{LiFe}_{1-y}\text{Ca}_y\text{PO}_4$) from Fe_2O_3



39

00484799-011800

$T_1 = 390$
10

(a) Pre-mix reactants in the following proportions

0.50 mol Li_2CO_3	=	36.95g
0.45 mol Fe_2O_3	=	71.86g
0.10 mol $\text{Ca}(\text{OH})_2$	=	7.41g
1.00 mol $(\text{NH}_4)_2\text{HPO}_4$	=	132.06g
0.45 mol carbon	=	5.40g

(100% excess carbon \rightarrow 10.80g)

(b) Pelletize powder mixture

10

(c) Heat to 750°C at a rate of $2^\circ/\text{minute}$ in argon.
Hold for 8 hours dwell at 750°C in argon

(d) Cool at a rate of $2^\circ/\text{minute}$

(e) Powderize pellet.

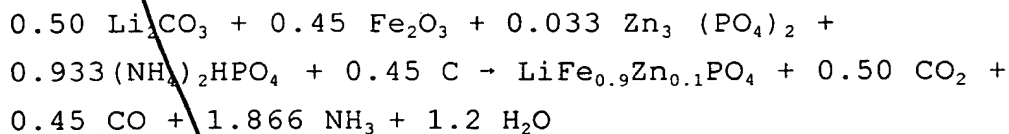
EXAMPLE VIII

15

Reaction 4

Formation of $\text{LiFe}_{0.9}\text{Zn}_{0.1}\text{PO}_4$

$(\text{LiFe}_{1-y}\text{Zn}_y\text{PO}_4)$ from Fe_2O_3 .



20

Pre-mix reactants in the following proportions

0.50 mol Li_2CO_3	=	36.95g
0.45 mol Fe_2O_3	=	71.86g
0.033 mol $\text{Zn}_3(\text{PO}_4)_2$	=	12.74g
0.933 mol $(\text{NH}_4)_2\text{HPO}_4$	=	123.21g

0.45 mol carbon = 5.40g

(100% excess carbon - 10.80g)

(b) Pelletize powder mixture

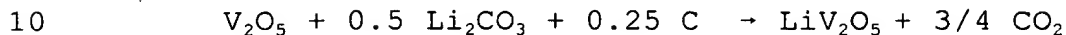
(c) Heat to 750°C at a rate of 2°/minute in argon.
Hold for 8 hours dwell at 750°C in argon

(d) Cool at a rate of 2°/minute

(e) Powderize pellet.

EXAMPLE IX

Reaction 5. Formation of gamma-LiV₂O₅ (γ)



(a) Pre-mix alpha V₂O₅, Li₂CO₃ and Shiwinigan Black (carbon) using ball mix with suitable media. Use a 25% weight excess of carbon over the reaction amounts above. For example, according to reaction above:

Need:	1 mol V ₂ O ₅	181.88g
	0.5 mol Li ₂ CO ₃	36.95g
	0.25 mol carbon	3.00g

(but use 25% excess carbon - 3.75g)

T, 0410

(b) Pelletize powder mixture

(c) Heat pellet to 600°C in flowing argon (or other inert atmosphere) at a heat rate of approximately 2°/minute. Hold at 600°C for about 60 minutes.

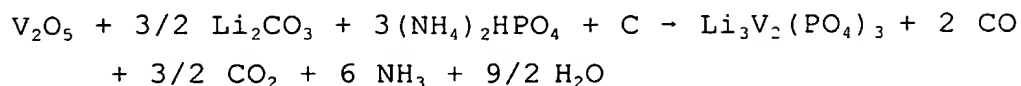
(d) Allow to cool to room temperature in argon at cooling rate of about 2°/minute.

(e) Powderize pellet using mortar and pestle

This reaction is able to be conducted at a temperature in a range of about 400°C to about 650°C in argon as shown, and also under other inert atmospheres such as nitrogen or vacuum. This reaction at this temperature range is primarily $C \rightarrow CO_2$. Note that the reaction $C \rightarrow CO$ primarily occurs at a temperature over about 650°C (HT, high temperature); and the reaction $C \rightarrow CO_2$ primarily occurs at a temperature of under about 650°C (LT, low temperature). The reference to about 650°C is approximate and the designation "primarily" refers to the predominant reaction thermodynamically favored although the alternate reaction may occur to some extent.

EXAMPLE X

Reaction 6. Formation of $Li_3V_2(PO_4)_3$



- (a) Pre-mix reactants above using ball mill with suitable media. Use a 25% weight excess of carbon. Thus,

1 mol V_2O_5	181.88g
3/2 mol Li_2CO_3	110.84g
3 mol $(NH_4)_2HPO_4$	396.18g
1 mol carbon	12.01g

(but use 25% excess carbon - 15.01g)

- (b) Pelletize powder mixture

- 10 (c) Heat pellet at 2°/minute to 300°C to remove CO_2 (from Li_2CO_3) and to remove NH_3 , H_2O . Heat in an inert atmosphere (e.g. argon). Cool to room temperature.

- (d) Powderize and repelletize

- 15 (e) Heat pellet in inert atmosphere at a rate of 2°C/minute to 850°C. Dwell for 8 hours at 850°C

- (f) Cool to room temperature at a rate of 2°/minute in argon.

- 20 (e) Powderize

This reaction is able to be conducted at a temperature in a range of about 700°C to about 950°C in argon as shown, and also under other inert atmospheres such as nitrogen or vacuum. A reaction temperature greater than about 670°C ensures C - CO reaction is primarily carried out.

**Characterization of Active Materials
and Formation and Testing of Cells**

Referring to **Figure 1**, the final product LiFePO_4 , prepared from Fe_2O_3 metal compound per Reaction 1(b), appeared brown/black in color. This olivine material product included carbon that remained after reaction. Its $\text{CuK}\alpha$ x-ray diffraction pattern contained all of the peaks expected for this material as shown in **Figure 1**. The pattern evident in **Figure 1** is consistent with the single phase olivine phosphate, LiFePO_4 . This is evidenced by the position of the peaks in terms of the scattering angle 2θ (theta), x axis. The x-ray pattern showed no peaks due to the presence of precursor oxides indicating that the solid state reaction is essentially entirely completed. Here the space group $\text{SG} = \text{pnma}$ (62) and the lattice parameters from XRD refinement are consistent with the olivine structure. The values are $a = 10.2883\text{\AA}$ (0.0020), $b = 5.9759$ (0.0037), $c = 4.6717\text{\AA}$ (0.0012) 0.0072, cell volume = 287.2264\AA^3 (0.0685). Density, $\rho = 3.605$ g/cc, zero = 0.452 (0.003). Peak at full width half maximum, PFWHM = 0.21. Crystallite size from XRD data = 704\AA .

The x-ray pattern demonstrates that the product of the invention was indeed the nominal formula LiFePO_4 . The term "nominal formula" refers to the fact that the relative proportion of atomic species may vary slightly on the order of 2 percent to 5 percent, or more typically, 1 percent to 3 percent, and that some portion of P may be substituted by Si, S or As; and some portion of O may be substituted by halogen, preferably F.

The LiFePO_4 , prepared as described immediately above, was tested in an electrochemical cell. The positive electrode was prepared as described above, using 19.0mg of active material. The positive electrode
5 contained, on a weight % basis, 85% active material, 10% carbon black, and 5% EPDM. The negative electrode was metallic lithium. The electrolyte was a 2:1 weight ratio mixture of ethylene carbonate and dimethyl carbonate within which was dissolved 1 molar LiPF_6 . The cells were
10 cycled between about 2.5 and about 4.0 volts with performance as shown in **Figures 2 and 3**.

Figure 2 shows the results of the first constant current cycling at 0.2 milliamps per square centimeter between about 2.5 and 4.0 volts based upon
15 about 19 milligrams of the LiFePO_4 active material in the cathode (positive electrode). In an as prepared, as assembled, initial condition, the positive electrode active material is LiFePO_4 . The lithium is extracted from the LiFePO_4 during charging of the cell. When fully
20 charged, about 0.72 unit of lithium had been removed per formula unit. Consequently, the positive electrode active material corresponds to $\text{Li}_{1-x}\text{FePO}_4$ where x appears to be equal to about 0.72, when the cathode material is at 4.0 volts versus Li/Li^+ . The extraction represents
25 approximately 123 milliamp hours per gram corresponding to about 2.3 milliamp hours based on 19 milligrams active material. Next, the cell is discharged whereupon a quantity of lithium is re-inserted into the LiFePO_4 . The re-insertion corresponds to approximately 121 milliamp
30 hours per gram proportional to the insertion of essentially all of the lithium. The bottom of the curve corresponds to approximately 2.5 volts. The total

45

cumulative capacity demonstrated during the entire extraction-insertion cycle is 244mAh/g.

Figure 3 presents data obtained by multiple constant current cycling at 0.2 milliamp hours per square centimeter of the LiFePO_4 versus lithium metal counter electrode between 2.5 and 4.0 volts. Data is shown for two temperatures, 23°C and 60°C. **Figure 3** shows the excellent rechargeability of the LiFePO_4 cell, and also shows good cycling and capacity of the cell. The performance shown after about 190 to 200 cycles is good and shows that electrode formulation is very desirable.

Referring to **Figure 4**, there is shown data for the final product $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$, prepared from the metal compounds Fe_2O_3 and $\text{Mg}(\text{OH})_2 \rightarrow \text{Mg}(\text{OH})_2$, per Reaction 2(b). Its $\text{CuK}\alpha$ x-ray diffraction pattern contained all of the peaks expected for this material as shown in **Figure 4**. The pattern evident in **Figure 4** is consistent with the single phase olivine phosphate compound, $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$. This is evidenced by the position of the peaks in terms of the scattering angle 2θ (theta), x axis. The x-ray pattern showed no peaks due to the presence of precursor oxides indicating that the solid state reaction is essentially entirely completed. Here the space group SG = Pnma (62) and the lattice parameters from XRD refinement are consistent with the olivine structure. The values are $a = 10.2688\text{\AA}$ (0.0069), $b = 5.9709\text{\AA}$ (0.0072), $c = 4.6762\text{\AA}$ (0.0054), cell volume = 286.7208\AA^3 (0.04294), $\rho = 3.617\text{ g/cc}$, zero = 0.702 (0.003), PFWHM = 0.01, and crystallite = 950\AA .

The x-ray pattern demonstrates that the product of the invention was indeed the nominal formula

LiFe_{0.9}Mg_{0.1}PO₄. The term "nominal formula" refers to the fact that the relative proportion of atomic species may vary slightly on the order of 2 percent to 5 percent, or more typically, 1 percent to 3 percent, and that some substitution of P and O may be made while maintaining the basic olivine structure.

The LiFe_{0.9}Mg_{0.1}PO₄, prepared as described immediately above, was tested in an electrochemical cell. The positive electrode was prepared as described above, using 18.9mg of active materials. The positive electrode, negative electrode and electrolyte were prepared as described earlier and in connection with **Figure 1**. The cell was between about 2.5 and about 4.0 volts with performance as shown in **Figures 4, 5 and 6**.

Figure 5 shows the results of the first constant current cycling at 0.2 milliamps per square centimeter between about 2.5 and 4.0 volts based upon about 18.9 milligrams of the LiFe_{0.9}Mg_{0.1}PO₄ active material in the cathode (positive electrode). In an as prepared, as assembled, initial condition, the positive electrode active material is LiFe_{0.9}Mg_{0.1}PO₄. The lithium is extracted from the LiFe_{0.9}Mg_{0.1}PO₄ during charging of the cell. When fully charged, about 0.87 units of lithium have been removed per formula unit. Consequently, the positive electrode active material corresponds to Li_{1-x}Fe_{0.9}Mg_{0.1}PO₄ where x appears to be equal to about 0.87, when the cathode material is at 4.0 volts versus Li/Li⁺. The extraction represents approximately 150 milliamp hours per gram corresponding to about 2.8 milliamp hours based on 18.9 milligrams active material. Next, the cell is discharged whereupon a quantity of lithium is re-inserted into the LiFe_{0.9}Mg_{0.1}PO₄. The re-

00370"66248460

insertion corresponds to approximately 146 milliamp hours per gram proportional to the insertion of essentially all of the lithium. The bottom of the curve corresponds to approximately 2.5 volts. The total cumulative specific capacity over the entire cycle is 296 mAh/g. This material has a much better cycle profile than the LiFePO_4 . **Figure 5** ($\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$) shows a very well defined and sharp peak at about 150 mAh/g. In contrast, **Figure 2** (LiFePO_4) shows a very shallow slope leading to the peak at about 123 mAh/g. The Fe-phosphate (**Figure 2**) provides 123 mAh/g compared to its theoretical capacity of 170 mAh/g. This ratio of 123/170, 72% is relatively poor compared to the Fe/Mg-phosphate. The Fe/Mg-phosphate (**Figure 5**) provides 150 mAh/g compared to a theoretical capacity of 160, a ratio of 150/160 or 94%.

Figure 6 presents data obtained by multiple constant current cycling at 0.2 milliamp hours per square centimeter of the $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ versus lithium metal counter electrode between 2.5 and 4.0 volts. **Figure 6** shows the excellent rechargeability of the $\text{Li}/\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ cell, and also shows good cycling and capacity of the cell. The performance shown after about 150 to 160 cycles is very good and shows that electrode formulation $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ performed significantly better than the LiFePO_4 . Comparing **Figure 3** (LiFePO_4) to **Figure 6** ($\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$) it can be seen that the Fe/Mg-phosphate maintains its capacity over prolonged cycling, whereas the Fe-phosphate capacity fades significantly.

Figure 7 shows the results of the first constant current cycling at 0.2 milliamps per square centimeter between about 2.5 and 4.0 volts based upon about 16 milligrams of the $\text{LiFe}_{0.8}\text{Mg}_{0.2}\text{PO}_4$ active material

in the cathode (positive electrode). In an as prepared, as assembled, initial condition, the positive electrode active material is $\text{LiFe}_{0.8}\text{Mg}_{0.2}\text{PO}_4$. The lithium is extracted from the $\text{LiFe}_{0.8}\text{Mg}_{0.2}\text{PO}_4$ during charging of the cell. When fully charged, about 0.79 units of lithium have been removed per formula unit. Consequently, the positive electrode active material corresponds to $\text{LiFe}_{0.8}\text{Mg}_{0.2}\text{PO}_4$ where x appears to be equal to about 0.79, when the cathode material is at 4.0 volts versus Li/Li^+ . The extraction approximately 140 milliamp hours per gram corresponding to about 2.2 milliamp hours based on 16 milligrams active material. Next, the cell is discharged whereupon a quantity of lithium is re-inserted into the $\text{LiFe}_{0.8}\text{Mg}_{0.2}\text{PO}_4$. The re-insertion corresponds to approximately 122 milliamp hours per gram proportional to the insertion of essentially all of the lithium. The bottom of the curve corresponds to approximately 2.5 volts. The total cumulative specific capacity over the entire cycle is 262 mAh/g.

Referring to **Figure 8**, there is shown data for the final product $\text{LiFe}_{0.9}\text{Ca}_{0.1}\text{PO}_4$, prepared from Fe_2O_3 and $\text{Ca}(\text{OH})_2$ by Reaction 3. Its $\text{CuK}\alpha$ x-ray diffraction pattern contained all of the peaks expected for this material as shown in **Figure 8**. The pattern evident in **Figure 8** is consistent with the single phase olivine phosphate compound, $\text{LiFe}_{0.9}\text{Ca}_{0.1}\text{PO}_4$. This is evidenced by the position of the peaks in terms of the scattering angle 2θ (theta), x axis. The x-ray pattern showed no peaks due to the presence of precursor oxides indicating that the solid state reaction is essentially entirely completed. Here the space group $\text{SG} = \text{Pnma}$ (62) and the lattice parameters from XRD refinement are consistent with olivine. The values are $a = 10.3240\text{\AA}$ (0.0045), $b =$

6.0042Å (0.0031), $c = 4.6887\text{\AA}$ (0.0020), cell volume =
 290.6370Å (0.1807), zero = 0.702 (0.003), $\rho = 3.62\text{ g/cc}$,
 PFWHM = 0.18, and crystallite = 680Å. The x-ray pattern
 demonstrates that the product of the invention was indeed
 the nominal formula $\text{LiFe}_{0.9}\text{Ca}_{0.1}\text{PO}_4$.

Figure 9 shows the results of the first
 constant current cycling at 0.2 milliamps per square
 centimeter between about 2.5 and 4.0 volts based upon
 about 18.5 milligrams of the $\text{LiFe}_{0.8}\text{Ca}_{0.2}\text{PO}_4$ active
 material in the cathode (positive electrode). In an as
 prepared, as assembled, initial condition, the positive
 electrode active material is $\text{LiFe}_{0.8}\text{Ca}_{0.2}\text{PO}_4$. The lithium
 is extracted from the $\text{LiFe}_{0.8}\text{Ca}_{0.2}\text{PO}_4$ during charging of
 the cell. When fully charged, about 0.71 units of
 lithium have been removed per formula unit.
 Consequently, the positive electrode active material
 corresponds to $\text{LiFe}_{0.8}\text{Ca}_{0.2}\text{PO}_4$ where x appears to be equal
 to about 0.71, when the cathode material is at 4.0 volts
 versus Li/Li^+ . The extraction represents approximately
 123 milliamp hours per gram corresponding to about 2.3
 milliamp hours based on 18.5 milligrams active material.
 Next, the cell is discharged whereupon a quantity of
 lithium is re-inserted into the $\text{LiFe}_{0.8}\text{Ca}_{0.2}\text{PO}_4$. The re-
 insertion corresponds to approximately 110 milliamp hours
 per gram proportional to the insertion of nearly all of
 the lithium. The bottom of the curve corresponds to
 approximately 2.5 volts. The total specific cumulative
 capacity over the entire cycle is 233 mAh/g.

Figure 10 shows the results of the first
 constant current cycling at 0.2 milliamps per square
 centimeter between about 2.5 and 4.0 volts based upon
 about 18.9 milligrams of the $\text{LiFe}_{0.8}\text{Zn}_{0.2}\text{PO}_4$ olivine active

50

004434799-04300

5 extracted from the $\text{LiFe}_{0.8}\text{Zn}_{0.2}\text{PO}_4$ during charging of the
cell. When fully charged, about 0.74 units of lithium
have been removed per formula unit. Consequently, the
positive electrode active material corresponds to $\text{Li}_{1-x}\text{Fe}_{0.8}\text{Zn}_{0.2}\text{PO}_4$ where x appears to be equal to about 0.74,
0 when the cathode material is at 4.0 volts versus Li/Li^+ .
The extraction represents approximately 124 milliamp
hours per gram corresponding to about 2.3 milliamp hours
based on 18.9 milligrams active material. Next, the cell
is discharged whereupon a quantity of lithium is re-
5 inserted into the $\text{LiFe}_{0.8}\text{Zn}_{0.2}\text{PO}_4$. The re-insertion
corresponds to approximately 108 milliamp hours per gram
proportional to the insertion of nearly all of the
lithium. The bottom of the curve corresponds to
approximately 2.5 volts.

51

The x-ray pattern demonstrates that the product of the invention was indeed the nominal formula gamma-

LiV_2O_5 . The term "nominal formula" refers to the fact that the relative proportion of atomic species may vary slightly on the order of 2 percent to 5 percent, or more typically, 1 percent to 3 percent.

5 The LiV_2O_5 prepared as described immediately above, was tested in an electrochemical cell. The cell was prepared as described above and cycled with performance as shown in **Figures 12 and 13**.

10 **Figure 12** shows the results of the first constant current cycling at 0.2 milliamps per square centimeter between about 2.8 and 3.8 volts based upon about 15.0 milligrams of the LiV_2O_5 active material in the cathode (positive electrode). In an as prepared, as assembled, initial condition, the positive electrode
15 active material is LiV_2O_5 . The lithium is extracted from the LiV_2O_5 during charging of the cell. When fully charged, about 0.93 unit of lithium had been removed per formula unit. Consequently, the positive electrode active material corresponds to $\text{Li}_{1-x}\text{V}_2\text{O}_5$ where x appears to
20 be equal to about 0.93, when the cathode material is at 3.8 volts versus Li/Li^+ . The extraction represents approximately 132 milliamp hours per gram corresponding to about 2.0 milliamp hours based on 15.0 milligrams active material. Next, the cell is discharged whereupon
25 a quantity of lithium is re-inserted into the LiV_2O_5 . The re-insertion corresponds to approximately 130 milliamp hours per gram proportional to the insertion of essentially all of the lithium. The bottom of the curve corresponds to approximately 2.8 volts.

30 **Figure 13** presents data obtained by multiple constant current cycling at 0.4 milliamp hours per square

52

008710" 65248460

centimeter (C/2 rate) of the LiV_2O_5 versus lithium metal counter electrode between 3.0 and 3.75 volts. Data for two temperature conditions are shown, 23°C and 60°C.

Figure 13 is a two part graph with **Figure 13A** showing the excellent rechargeability of the LiV_2O_5 . **Figure 13B** shows good cycling and capacity of the cell. The performance shown up to about 300 cycles is good.

Referring to **Figure 14**, the final product $\text{Li}_3\text{V}_2(\text{PO}_4)_3$, prepared by Reaction 6, appeared green/black in color. Its $\text{CuK}\alpha$ x-ray diffraction pattern contained all of the peaks expected for this material as shown in **Figure 14**. The pattern evident in **Figure 14** is consistent with a single phosphate compound $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ of the monoclinic, Nasicon phase. This is evidenced by the position of the peaks in terms of the scattering angle 2θ (theta), x axis. The x-ray pattern showed no peaks due to the presence of precursor oxides indicating that the solid state reaction is essentially entirely completed.

The x-ray pattern demonstrates that the product of the invention was indeed the nominal formula $\text{Li}_3\text{V}_2(\text{PO}_4)_3$. The term "nominal formula" refers to the fact that the relative proportion of atomic species may vary slightly on the order of 2 percent to 5 percent, or more typically, 1 percent to 3 percent; and that substitution of P and O may occur.

The $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ prepared as described immediately above, was tested in an electrochemical cell. The cell was prepared as described above, using 13.8mg of active material. The cell was prepared as described above and cycled between about 3.0 and about 4.2 volts using the EVS technique with performance as shown in **Figures 16 and**

53

17. **Figure 16** shows specific capacity versus electrode potential against Li. **Figure 17** shows differential capacity versus electrode potential against Li.

5 A comparative method was used to form
Li₃V₂(PO₄)₃. Such method was reaction without carbon and
under H₂-reducing gas as described in U.S. Patent No.
5,871,866. The final product, prepared as per U.S.
Patent No. 5,871,866, appeared green in color. Its CuKα
x-ray diffraction pattern contained all of the peaks
10 expected for this material as shown in **Figure 15**. The
pattern evident in **Figure 15** is consistent with a
monoclinic Nasicon single phase phosphate compound
Li₃V₂(PO₄)₃. This is evidenced by the position of the
peaks in terms of the scattering angle 2 θ (theta), x
15 axis. The x-ray pattern showed no peaks due to the
presence of precursor oxides indicating that the solid
state reaction is essentially entirely completed.
Chemical analysis for lithium and vanadium by atomic
absorption spectroscopy showed, on a percent by weight
20 basis, 5.17 percent lithium and 26 percent vanadium. This
is close to the expected result of 5.11 percent lithium
and 25 percent vanadium.

The chemical analysis and x-ray patterns of
Figures 14 and 15 demonstrate that the product of **Figure**
25 **14** was the same as that of **Figure 15**. The product of
Figure 14 was prepared without the undesirable H₂
atmosphere and was prepared by the novel carbothermal
solid state synthesis of the invention.

Figure 16 shows a voltage profile of the test
30 cell, based on the Li₃V₂(PO₄)₃ positive electrode active
material made by the process of the invention and as

characterized in **Figure 14**. It was cycled against a lithium metal counter electrode. The data shown in **Figure 16** is based on the Electrochemical Voltage Spectroscopy (EVS) technique. Electrochemical and kinetic data were recorded using the Electrochemical Voltage Spectroscopy (EVS) technique. Such technique is known in the art as described by J. Barker in Synth, Met 28, D217 (1989); Synth. Met. 32, 43 (1989); J. Power Sources, 52, 185 (1994); and Electrochimica Acta, Vol. 40, No. 11, at 1603 (1995). **Figure 16** clearly shows and highlights the reversibility of the product. The positive electrode contained about 13.8 milligrams of the $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ active material. The positive electrode showed a performance of about 133 milliamp hours per gram on the first discharge. In **Figure 16**, the capacity in, and the capacity out are essentially the same, resulting in essentially no capacity loss. **Figure 17** is an EVS differential capacity plot based on **Figure 16**. As can be seen from **Figure 17**, the relatively symmetrical nature of peaks indicates good electrical reversibility, there are small peak separations (charge/discharge), and good correspondence between peaks above and below the zero axis. There are essentially no peaks that can be related to irreversible reactions, since all peaks above the axis (cell charge) have corresponding peaks below the axis (cell discharge), and there is essentially no separation between the peaks above and below the axis. This shows that the carbothermal method of the invention produces high quality electrode material.

Figure 18 presents data obtained by multiple constant current cycling at 0.2 milliamp hours per square centimeter of the $\text{LiFe}_{0.8}\text{Mg}_{0.2}\text{PO}_4$ versus lithium metal counter electrode between 2.5 and 4.0 volts. **Figure 18**

55

shows the excellent rechargeability of the
Li/LiFe_{0.8}Mg_{0.2}PO₄ cell, and also shows good cycling and
capacity of the cell. The performance shown after about
110 to 120 cycles at 23°C is very good and shows that
5 electrode formulation LiFe_{0.8}Mg_{0.2}PO₄ performed
significantly better than the LiFePO₄. The cell cycling
test at 60°C was started after the 23°C test and was
ongoing. Comparing **Figure 3** (LiFePO₄) to **Figure 18**
(LiFe_{0.8}Mg_{0.2}PO₄), it can be seen that the Fe/Mg-phosphate
10 maintains its capacity over prolonged cycling, whereas
the Fe-phosphate capacity fades significantly.

In addition to the above cell tests, the active
materials of the invention were also cycled against
insertion anodes in non-metallic, lithium ion, rocking
15 chair cells.

The lithium mixed metal phosphate and the
lithium metal oxide were used to formulate a cathode
electrode. The electrode was fabricated by solvent
casting a slurry of the treated, enriched lithium
20 manganese oxide, conductive carbon, binder, plasticizer
and solvent. The conductive carbon used was Super P (MMM
Carbon). Kynar Flex 2801® was used as the binder and
electronic grade acetone was used as a solvent. The
preferred plasticizer was dibutyl phthalate (DPB). The
25 slurry was cast onto glass and a free-standing electrode
was formed as the solvent was evaporated. In this
example, the cathode had 23.1mg LiFe_{0.9}Mg_{0.1}PO₄ active
material. Thus, the proportions are as follows on a
percent weight basis: 80% active material; 8% Super P
30 carbon; and 12% Kynar binder.

A rocking chair battery was prepared comprising the anode, the cathode, and an electrolyte. The ratio of the active cathode mass to the active anode mass was about 2.14:1. The two electrode layers were arranged with an electrolyte layer in between, and the layers were laminated together using heat and pressure as per the Bell Comm. Res. patents incorporated herein by reference earlier. In a preferred method, the cell is activated

57

with EC/DMC solvent in a weight ratio of 2:1 in a solution containing 1 M LiPF_6 salt.

Figures 19 and 20 show data for the first four complete cycles of the lithium ion cell having the $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ cathode and the MCMB2528 anode. The cell comprised 23.1mg active $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ and 10.8mg active MCMB2528 for a cathode to anode mass ratio of 2.14. The cell was charged and discharged at 23°C at an approximate C/10 (10 hour) rate between voltage limits of 2.50 V and 3.60 V. The voltage profile plot (**Figure 19**) shows the variation in cell voltage versus time for the $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ /MCMB2528 lithium ion cell. The symmetrical nature of the charge-discharge is clearly evident. The small degree of voltage hysteresis between the charge and discharge processes is evidence for the low overvoltage in the system, which is very good. **Figure 20** shows the variation of $\text{LiFe}_{0.9}\text{Mg}_{0.1}\text{PO}_4$ specific capacity with cycle number. Clearly, over the cycles shown, the material demonstrates good cycling stability.

Figure 21 shows data for the first three complete cycles of the lithium ion cell having the gamma- LiV_2O_5 cathode and the MCMB2528 anode. The cell prepared was a rocking chair, lithium ion cell as described above. The cell comprised 29.1mg gamma- LiV_2O_5 cathode active material and 12.2mg MCMB2528 anode active material, for a cathode to anode mass ratio of 2.39. As stated earlier, the liquid electrolyte used was EC/DMC (2:1) and 1M LiPF_6 . The cell was charged and discharged at 23°C at an approximate C/10 (10 hour) rate between voltage limits of 2.50 V and 3.65 V. The voltage profile plot (**Figure 21**) shows the variation in cell voltage versus time for the LiV_2O_5 /MCMB2528 lithium ion cell. The symmetrical nature

of the charge-discharge is clearly evident. The small degree of voltage hysteresis between the charge and discharge processes is evidence for the low overvoltage in the system, which is very good.

5

In summary, the invention provides new compounds $\text{Li}_a\text{MI}_b\text{MII}_c(\text{PO}_4)_d$ and $\gamma\text{-LiV}_2\text{O}_5$ by new methods which are adaptable to commercial scale production. The $\text{Li}_1\text{MI}_{1-y}\text{MII}_y\text{PO}_4$ compounds are isostructural olivine compounds as demonstrated by XRD analysis. Substituted compounds, such as $\text{LiFe}_{1-y}\text{Mg}_y\text{PO}_4$ show better performance than LiFePO_4 unsubstituted compounds when used as electrode active materials. The method of the invention utilizes the reducing capabilities of carbon along with selected precursors and reaction conditions to produce high quality products suitable as electrode active materials or as ion conductors. The reduction capability of carbon over a broad temperature range is selectively applied along with thermodynamic and kinetic considerations to provide an energy-efficient, economical and convenient process to produce compounds of a desired composition and structure. This is in contrast to known methods.

Principles of carbothermal reduction have been applied to produce pure metal from metal oxides by removal of oxygen. See, for example, U.S. Patent Nos. 2,580,878, 2,570,232, 4,177,060, and 5,803,974. Principles of carbothermal and thermal reduction have also been used to form carbides. See, for example, U.S. Patent Nos. 3,865,745 and 5,384,291; and non-oxide ceramics (see U.S. Patent No. 5,607,297). Such methods are not known to have been applied to form lithiated products or to form products without oxygen abstraction

from the precursor. The methods described with respect to the present invention provide high quality products which are prepared from precursors which are lithiated during the reaction without oxygen abstraction. This is a
 5 surprising result. The new methods of the invention also provide new compounds not known to have been made before.

For example, $\alpha\text{-V}_2\text{O}_5$ is conventionally lithiated electrochemically against metallic lithium. Thus, $\alpha\text{-V}_2\text{O}_5$ is not suitable as a source of lithium
 10 for a cell. As a result, $\alpha\text{-V}_2\text{O}_5$ is not used in an ion cell. In the present invention, $\alpha\text{-V}_2\text{O}_5$ is lithiated by carbothermal reduction using a simple lithium-containing compound and the reducing capability of carbon to form a $\gamma\text{-LiV}_2\text{O}_5$. The single phase
 15 compound, $\gamma\text{-LiV}_2\text{O}_5$ is not known to have been directly and independently prepared before. There is not known to be a direct synthesis route. Attempts to form it as a single phase resulted in a mixed phase product containing one or more beta phases and having the formula $\text{Li}_x\text{V}_2\text{O}_5$
 20 with $0 < x \leq 0.49$. This is far different from the present single phase $\gamma\text{-Li}_x\text{V}_2\text{O}_5$ with x equal to one, or very close to one. The flexibility of the process of the present invention is such that it can be conducted over a wide temperature range. The higher the temperature, the
 25 more quickly the reaction proceeds. For example, at 650°C , conversion of $\alpha\text{-V}_2\text{O}_5$ to $\gamma\text{-LiV}_2\text{O}_5$ occurs in about one hour, and at 500° it takes about 8 hours. Here, about one quarter ($1/4$) atomic unit of carbon is used to reduce one atomic unit of vanadium, that is,
 30 $\text{V}^{5+}\text{V}^{5+}$ to $\text{V}^{5+}\text{V}^{4+}$. The predominate reaction is C to CO_2 where for each atomic unit of carbon at ground state zero, a plus 4 oxidation state results. Correspondingly, for each $1/4$ atomic unit of carbon, one atomic unit of

vanadium is reduced from V^{+5} to V^{+4} . (See Reaction 5).
The new product, gamma- LiV_2O_5 is air-stable and suitable
as an electrode material for an ion cell or rocking chair
battery.

5 The convenience and energy efficiency of the
present process can also be contrasted to known methods
for forming products under reducing atmosphere such as H_2
which is difficult to control, and from complex and
expensive precursors. In the present invention, carbon
10 is the reducing agent, and simple, inexpensive and even
naturally occurring precursors are useable. For example,
it is possible to produce $LiFePO_4$ from Fe_2O_3 , a simple
common oxide. (See Reaction 1b). The production of
 $LiFePO_4$ provides a good example of the thermodynamic and
15 kinetic features of the method. Iron phosphate is
reduced by carbon and lithiated over a broad temperature
range. At about $600^\circ C$, the C to CO_2 reaction
predominates and takes about a week to complete. At
about $750^\circ C$, the C to CO reaction predominates and takes
20 about 8 hours to complete. The C to CO_2 reaction
requires less carbon reductant but takes longer due to
the low temperature kinetics. The C to CO reaction
requires about twice as much carbon, but due to the high
temperature reaction kinetics, it proceeds relatively
25 fast. In both cases, the Fe in the precursor Fe_2O_3 has
oxidation state +3 and is reduced to oxidation (valence)
state +2 in the product $LiFePO_4$. The C to CO reaction
requires that $\frac{1}{2}$ atomic unit of carbon be used for each
atomic unit of Fe reduced by one valence state. The CO
30 to CO_2 reaction requires that $\frac{1}{4}$ atomic unit of carbon
be used for each atomic unit of Fe reduced by one valence
state.

61

00870" 66248460

09484799-01800

The active materials of the invention are also characterized by being stable in an as-prepared condition, in the presence of air and particularly humid air. This is a striking advantage, because it facilitates preparation of and assembly of battery cathodes and cells, without the requirement for controlled atmosphere. This feature is particularly important, as those skilled in the art will recognize that air stability, that is, lack of degradation on exposure to air, is very important for commercial processing. Air-stability is known in the art to more specifically indicate that a material does not hydrolyze in presence of moist air. Generally, air-stable materials are also characterized by Li being extracted therefrom above about 3.0 volts versus lithium. The higher the extraction potential, the more tightly bound the lithium ions are to the host lattice. This tightly bound property generally confers air stability on the material. The air-stability of the materials of the invention is consistent with the stability demonstrated by cycling at the conditions stated herein. This is in contrast to materials which insert Li at lower voltages, below about 3.0 volts versus lithium, and which are not air-stable, and which hydrolyze in moist air.

While this invention has been described in terms of certain embodiments thereof, it is not intended that it be limited to the above description, but rather only to the extent set forth in the following claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined in the following claims.

62